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Hydraulics of Culverts

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HYDRAULICS OF CULVERTS

BY

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THESIS

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This is to certify that the thesis of CHARLES WILLIAM BREMNER entitled HYDRAULICS OF CULVERTS was prepared under my personal supervision; and I recommend that it be approved as meeting this part of the requirements for the degree of Bachelor of Science in Civil Engineering.

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HYDRAULICS OF CULVERTS.

A culvert is an opening through a highway or railroad embankment to carry a small stream. Hydraulics of a culvert is the study of the laws of flow of water through the culvert. There are many kinds of culverts in use, some of which are pipe, arch, and box culverts. A box culvert, narrow with respect to height (6 in. x 4 ft.), has been used in the experimental work of this thesis. It was thought that this shape would allow better chance for observations with the rate of flow available, than one of more ordinary proportions.

There is very little known about the losses of head and the discharging capacity of culverts. The principles of the flow of water in long pipes and conduits are quite well established but they are not directly applicable to the flow in culverts. An investigation of the laws of discharge in culverts should therefore be of value.

Before going into this investigation it may be well to review the theoretical explanation of lost head. It is a well known fact that just after water enters into a culvert there is a decided drop in in the surface of the water and then a rise of the surface. The drop near the entrance is caused by entrance loss, velocity head, and friction loss. The friction loss, being so small for the short length considered, will be included in the entrance loss. An

equation in terms of effective heads will be used as follows:

$$h = h_1 + \frac{v_1^2}{2g} + h'.$$

where h' is the lost entrance head and is equal to $e\frac{v_e^2}{2g}$.

Therefore transposing and substituting for h

$$h - h_1 = \frac{v_1^2}{2g} + e\frac{v_e^2}{2g}$$

or

$$D = \frac{v_1^2}{2g} + e\frac{v_e^2}{2g}.$$

in which D is the lost head between the surface of the water before it enters the culvert and any section under consideration; v_e is taken at the entrance and e is the coefficient of entrance head; $\frac{v_1^2}{2g}$ is the amount of lost head in imparting velocity to the water v being taken at the section considered. (See Fig. 1)

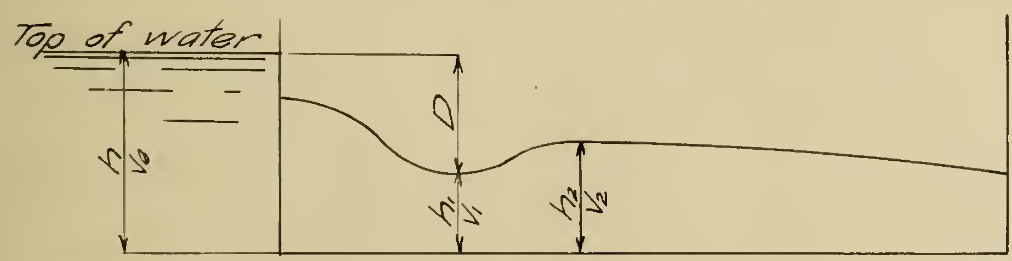


Fig. 1.

Since there have been no experiments performed on the hydraulics of culverts, it was a question as to the best method of procedure in getting data for these experiments. At first the Boneyard seemed to be the only available place where enough water could be

supplied to flow through the culvert, but the difficulty of the measurement and the control of the flow caused this plan to be abandoned. The proposed plan was to construct a culvert across the stream in such a manner that different sized openings and shapes could be studied, the wings of the culvert were to be built up of 2" x 8" board pile sheating, held in place by 4" x 4" posts, driven into the bed of the stream. After a close inspection of the banks of the stream and running levels the writer decided to build the culvert fifty feet west of the west line of the Mathews Avenue bridge, and a design for a simple wooden culvert to use for experimental work was made as shown in Fig.2. The culvert was to be about twenty feet long and open on the top, so as to obtain readings to the water surface. By this method the water could be backed up possibly to a four foot head and the depth regulated by a sluice gate through which the unnecessary water could be run out. The culverts to be installed were square, rectangular, and round diameters of four feet. The cost for the material and construction would have been rather expensive.

In the hydraulics laboratory the supply of water could be maintained constant by means of pumps until an experiment was finished, and then another rate of flow could be obtained. It seemed, therefore, to be the best place to make the experiments.

The apparatus, as shown in the picture, was set up according to the plans in Fig. 3. To obtain the quantity of water flowing through the culvert, vertical jets(8 inches and 10 inches in diameter) were used. The water fell into a catcher and ran off into a box in which two baffle boards were set, so as to lessen the splash and cause a more even flow into the mouth of

the culvert. The culvert was 13 1/2 ft. long and six inches wide. It would have been better to use a culvert 9 inches or a foot wide to obtain a steadier flow of water. In calculating the quantity of water used the formula $Q = ca\sqrt{2gh}$ was used. c is a constant value which is different for the different sizes of jets used. For the 8 inch jet c = .65, and for the 10 inch, c = .66. a is the area of the orifice in square feet. h is the height of the jet of water above the face of the orifice plate in feet, and g is the acceleration of gravity (32.2 ft. per second). A curve as shown in Plate A was plotted in which Q for any height of jet could be read directly for both the 8 inch and 10 inch nozzles.

Measurements of the surface of the water for various discharges were made by using a folding ruler and measuring from the top of culvert to the top of water. For the first 7 feet, the culvert top was 4 ft. above the bottom but from 7 1/2 ft. to the end the top of culvert was only 3' - 1 1/2" inches above the bottom of the culvert. Elevations were taken of the surface of the water before entering the culvert, and every half of a foot from the entrance to the end, - a set of elevations for each discharge. These measurements were first taken when the outlet was free and when an obstruction one foot deep was placed at the end so as to act the same as if water backed up the flow through the culvert. This caused a more steady flow and lessened the drop of water at the entrance considerably. The water came out of the end as shown in Fig. 4.

Experiments were also made with the entrance to culvert 2 ft., 1 1/2 ft., and 1 ft. deep. Readings were also taken with

backwater conditions with the 2 ft. entrance.

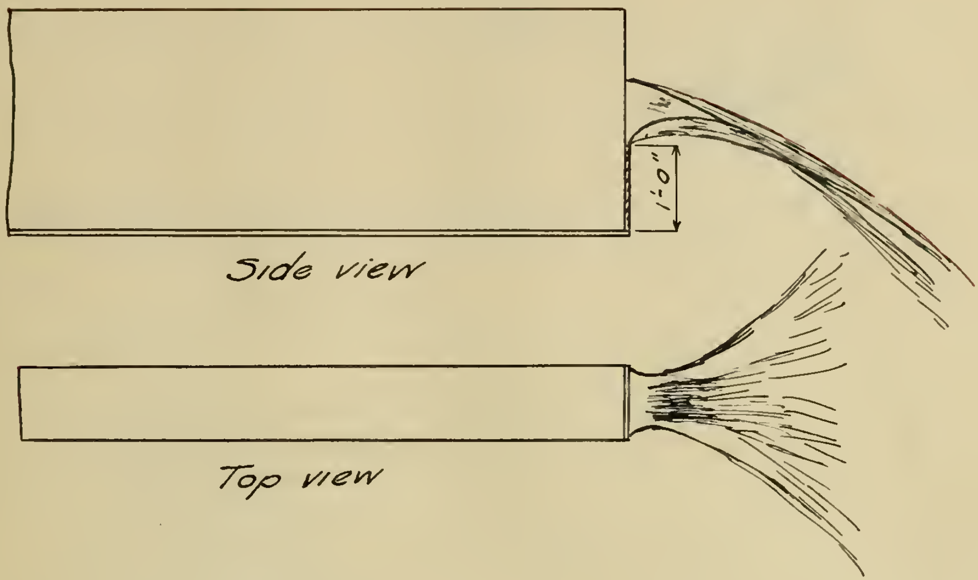


Fig. 4.

It was rather difficult to obtain readings for the 1 1/2 ft. and 1 ft. entrances as the water came through the opening with such velocity that the water foamed and splattered and the exact surface near the entrance could not be noted.

There were several errors which modified the results, and which caused the wide variation of the value of entrance coefficient, as shown in the tables. First, the leakage from cracks in the catcher and culvert was quite large and some water escaped by splashing over the edge of the box as it fell from the catcher. Second, the surface of the water was not quiet or even enough to obtain accurate readings of the water surface with the rule, and the variations in results are due to this error more than the others. Third, the height of the jet of water coming through the orifice could not be accurately determined, as the action of the pumping caused a slight pulsation of the jet. The reading was obtained by sighting across the top of the jet from one scale to

another as shown in Fig. 5. However, the error in figuring the discharge was slight, and this method of obtaining the quantity of water flowing proved very satisfactory.

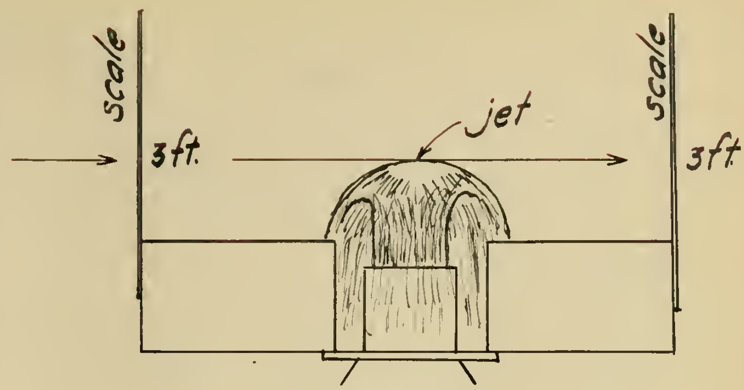


Fig. 5.

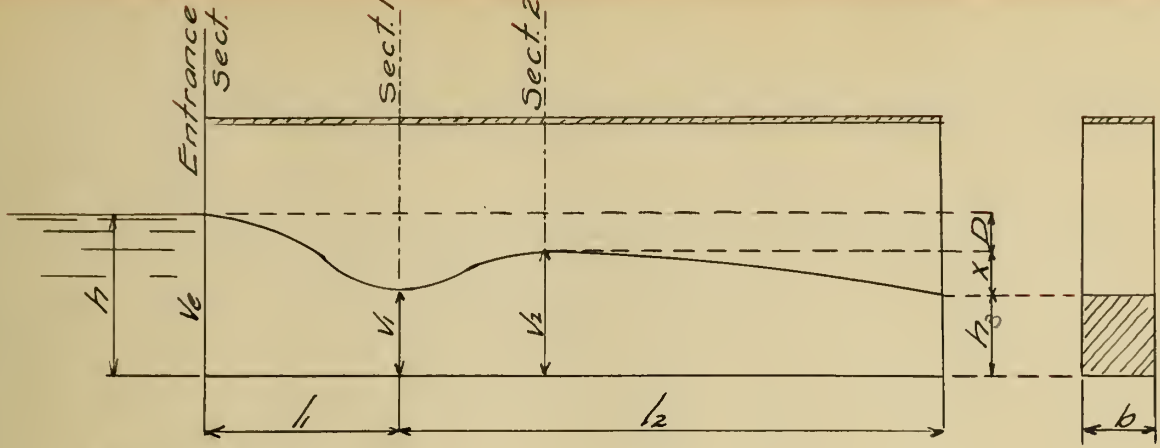
In figuring out the values of the coefficients e_1 and e_2 with respect to sections 1 and 2 respectively, the velocities were taken as the average at those sections and figured out from the formula $Q = av$ where Q = the discharge in cu. ft. per sec., a = the area in square feet for the section under consideration, and v is the velocity in feet per second at that section. Lack of time prevented Pitot tube readings to determine actual distribution of velocities in different cross sections of the culvert.

The entrance coefficients e_1 and e_2 seem to vary widely for the different conditions of discharge considered. As has been said before, this may be due to the error in determining elevation of the surface of the water. The average value of e_1 seems to be about one, and this value of e_1 is recommended for use.

Solution of Typical Problems.-The solutions of several problems which arise in the discussion of flow of water in culverts are given below.

PROBLEM I.

Given depth of back-water and rate of discharge in a level culvert not flowing full, to determine depth of headwater.



We have Q = av

a in this problem = bh

therefore $v_3 = \dfrac{Q}{bh}$

$v_2 = v_3$ approximately (except in long culverts)

From Chezy's formula

$$v_3 = c\sqrt{rs} = c\sqrt{\frac{bh}{b+2h} \cdot \frac{x}{l_2}}$$

$$v_3^2 = c^2 \frac{bh}{b+2h} \cdot \frac{x}{l_2}$$

$$x = \frac{v_3^2 \; l_2(b+2h)}{c^2 \; bh} \qquad (1)$$

Determine c from Kutter's formula using a value of n depending upon conditions. The value of x determined by equation (1) is too high because the value of v_3 is greater than the average velocity. If x is too large, a second solution may be made by using an average between v_2 and v_3. The value of v_2 is $\dfrac{Q}{b(h+x)}$. A more nearly correct value of x may be determined by this solution.

Experiments show that the drop between entrance and section 2 can be approximately expressed by

$$D = e\frac{v_e^2}{2g} + \frac{v_2^2}{2g} \qquad (2)$$

Taking e = 1.00 and $v_e = \dfrac{Q}{(h + x + D)b}$

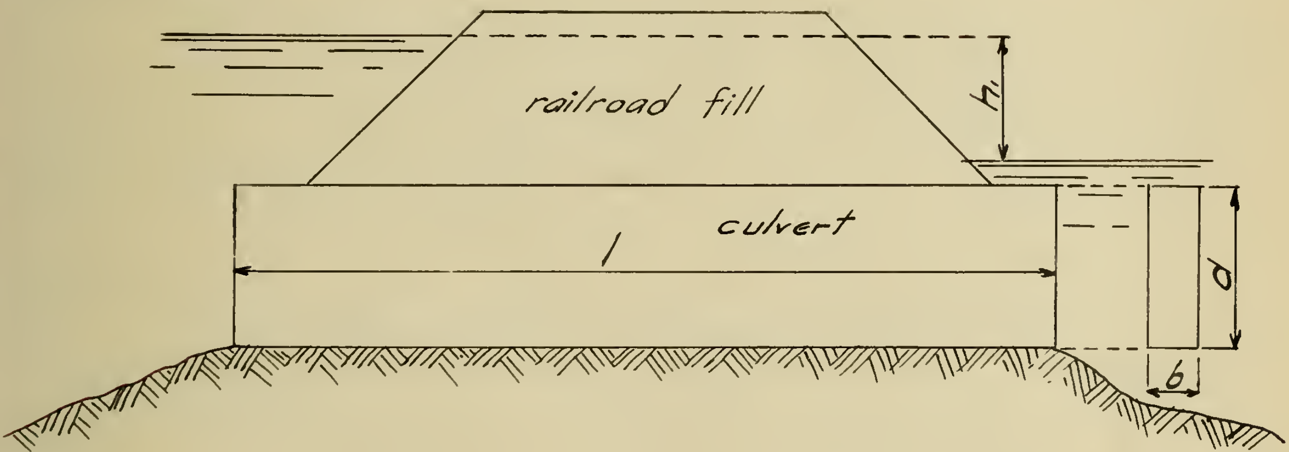
A value of D can be formed by trial satisfying equation (2) and the condition for e .

Since this gives the values of the heads used to make up the depth of headwater (H), the equation is

$$H = h + x + d. \qquad (3)$$

PROBLEM 2.

Backwater level with roof of culvert, or higher, to determine the depth of head-water above backwater with a given rate of discharge.



$$v = \frac{Q}{bd}$$

$$v = c\sqrt{rs} = c\sqrt{\frac{bd}{2(b+d)} \cdot \frac{h'}{l}}$$

Find c from Kutter's formula using a value of n depending upon conditions. h' is the velocity lost head.

$$\frac{Q}{bd} = c\sqrt{\frac{bd}{2(b+d)} \cdot \frac{h'}{l}}$$

$$h' = \frac{2Q^2 l\,(b + d)}{c^2 b^3 d^3} \qquad (1)$$

The entrance loss $h_e = e\,\dfrac{v_e^2}{2g}$

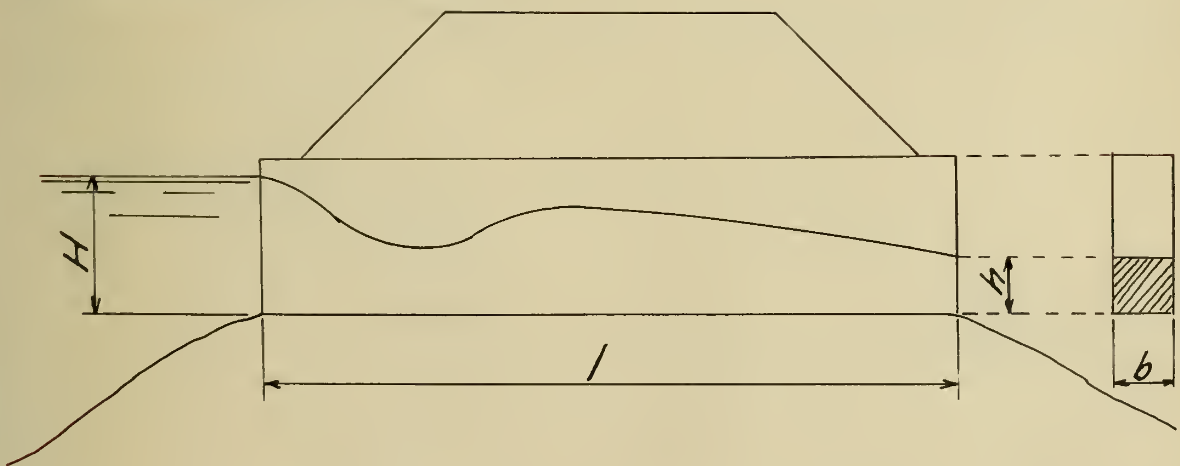
$$v_e = v$$

$$h_e = e\,\frac{v_e^2}{2g} = e\,\frac{v^2}{2g} = e\,\frac{Q^2}{2b^2 d^2 g} \qquad (2)$$

and $h_l = h' + h_e \qquad (3)$

PROBLEM 3.

Given the elevations of head water and backwater and size of culvert to determine rate of flow, both headwater and backwater being below top of culvert.



This problem must be solved by trial.

To determine Q approximately substitute in Chezy's formula to determine average velocity. Use

$$s = \frac{H - h}{l}$$

and

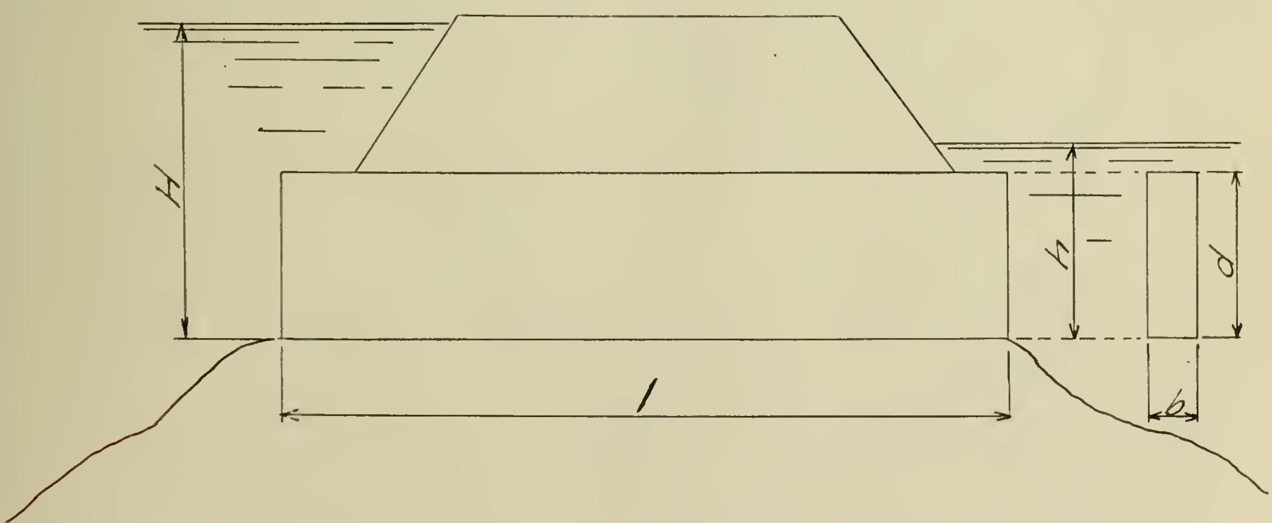
$$r = \frac{\frac{H + h}{2}\, b}{b + H + h} = \frac{(H + h)\, b}{2\,(b + H + h)}$$

$$Q = av = \left(\frac{H + h}{2}\, b\right) v$$

With this value of Q solve as in Problem I and determine difference of elevation of headwater and backwater. If this differs from H - h and the value of Q may be assumed and the solution again gone through until the actual and computed values are in agreement.

PROBLEM 4.

<u>Given the elevations of headwater and backwater and size of culvert to determine rate of flow, both headwater and backwater above top of culvert.</u>



$$v = c\sqrt{rs} = c\sqrt{r\frac{h'}{l}}$$

$$v^2 = c^2 r \frac{h'}{l}$$

Therefore,

$$h' = \frac{v^2 l}{c^2 r}$$

$$H - h = e\frac{v_e^2}{2g} + \frac{v^2 l}{c^2 r} + \frac{v^2}{2g}$$

Take $e = 1$,

$$H - h = \frac{v^2}{2g}\left(1 + \frac{2gl}{c^2 r} + 1\right) = \frac{v^2}{2g}\left(2 + \frac{2gl}{c^2 r}\right)$$

Therefore,

$$v = \sqrt{\frac{2g(H - h)}{2 + \frac{2gl}{c^2 r}}}$$

And

$$Q = av = bd\sqrt{\frac{2g(H - h)}{2 + \frac{2gl}{c^2 r}}}.$$

PLAN FOR CULVERT IN THE
BONEYARD 50 FEET WEST OF
MATHEWS AVENUE BRIDGE
Scale 1in. = 2 ft.   C.W.B.

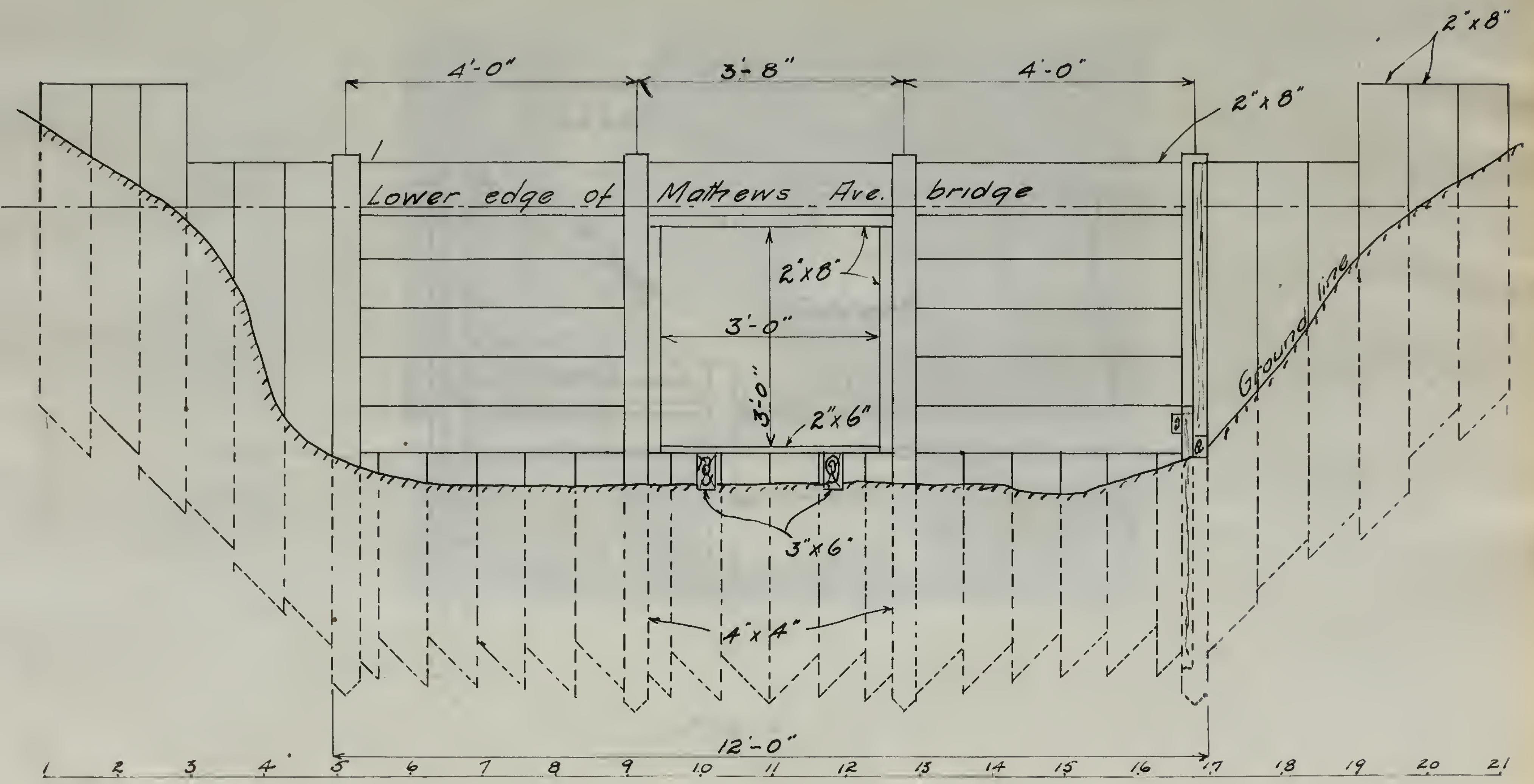


Fig. 2

Plan for Culvert in the Boneyard 50 feet west of Mathews Avenue Bridge Scale 1in=2ft. C.H.B

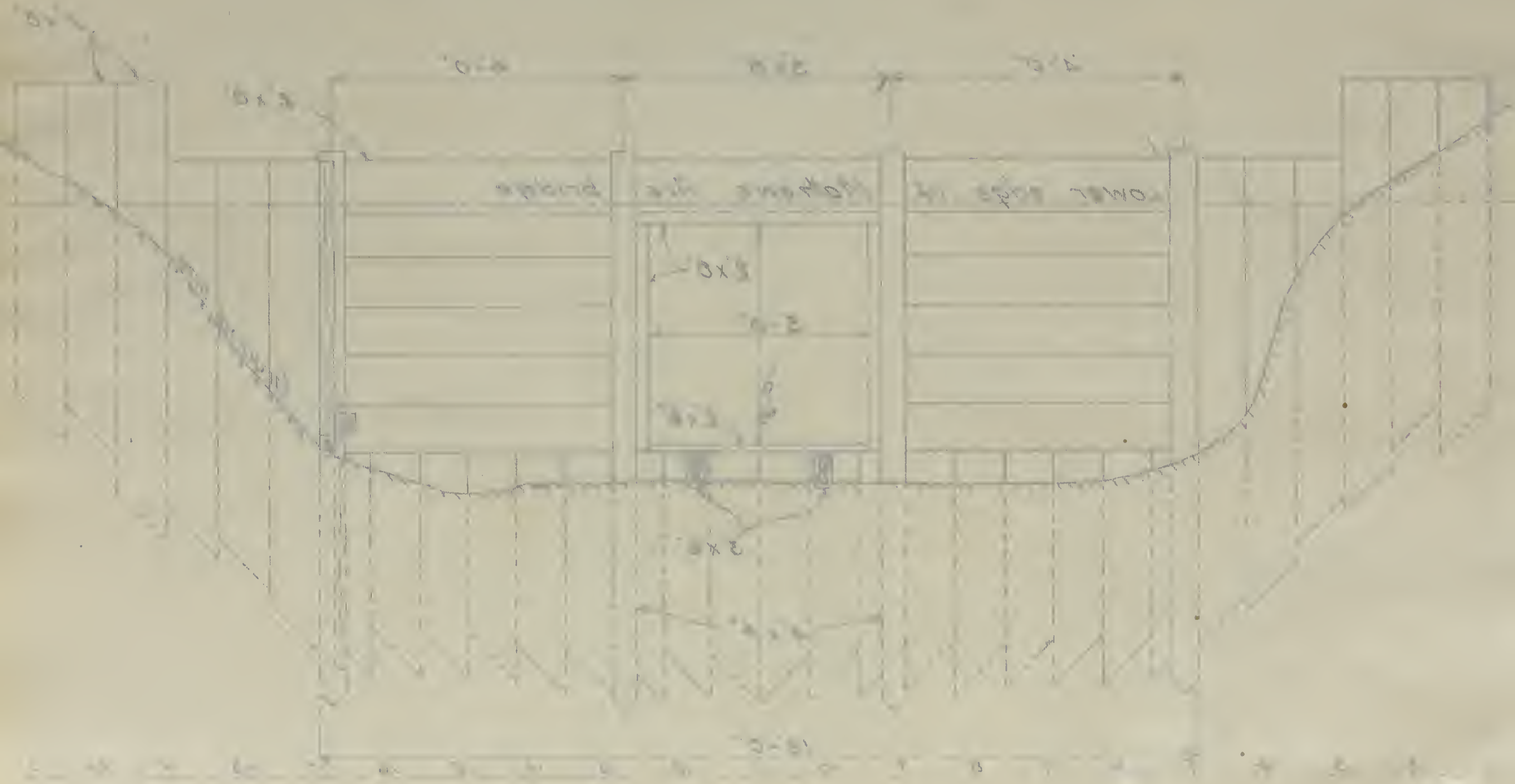


Fig 2

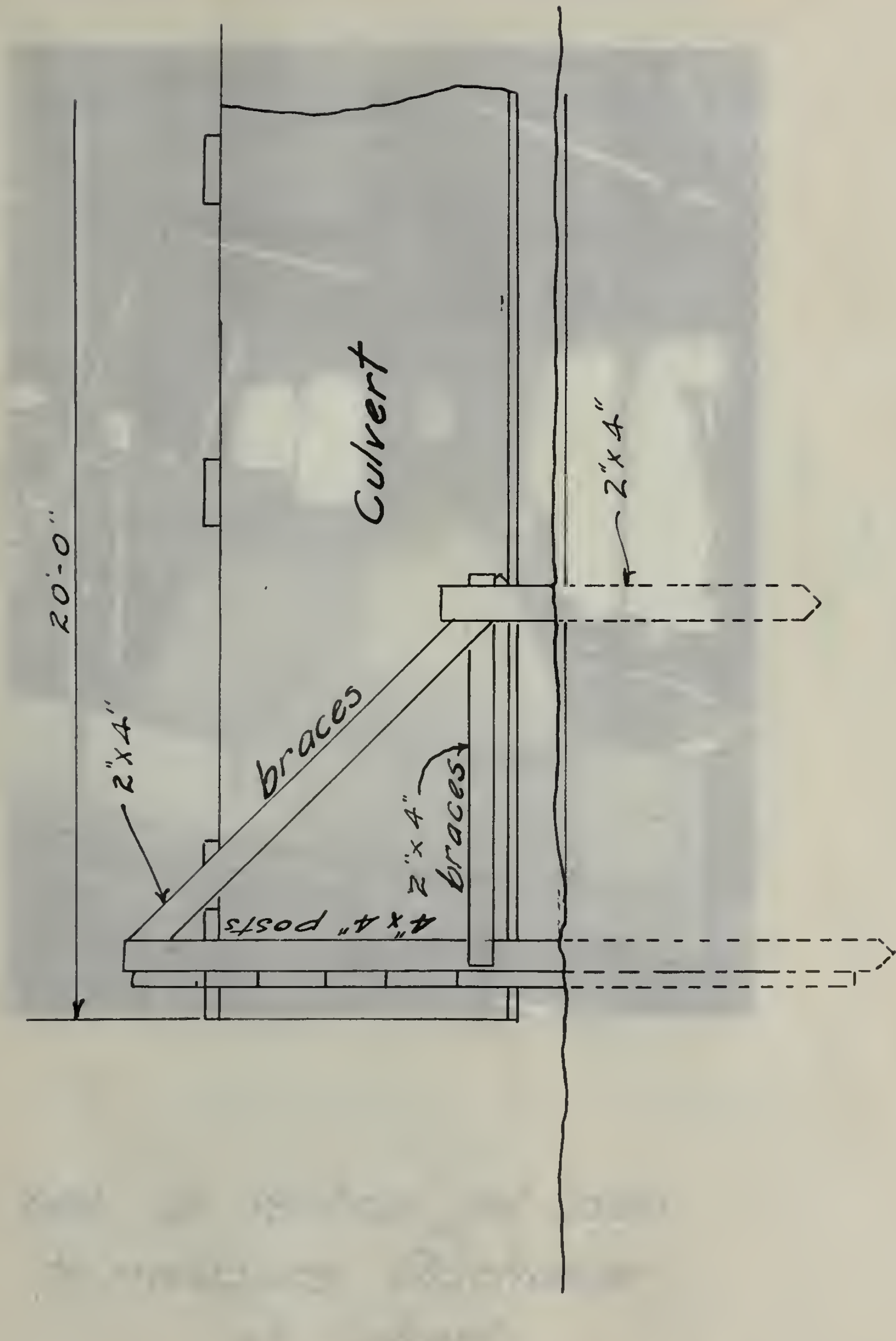
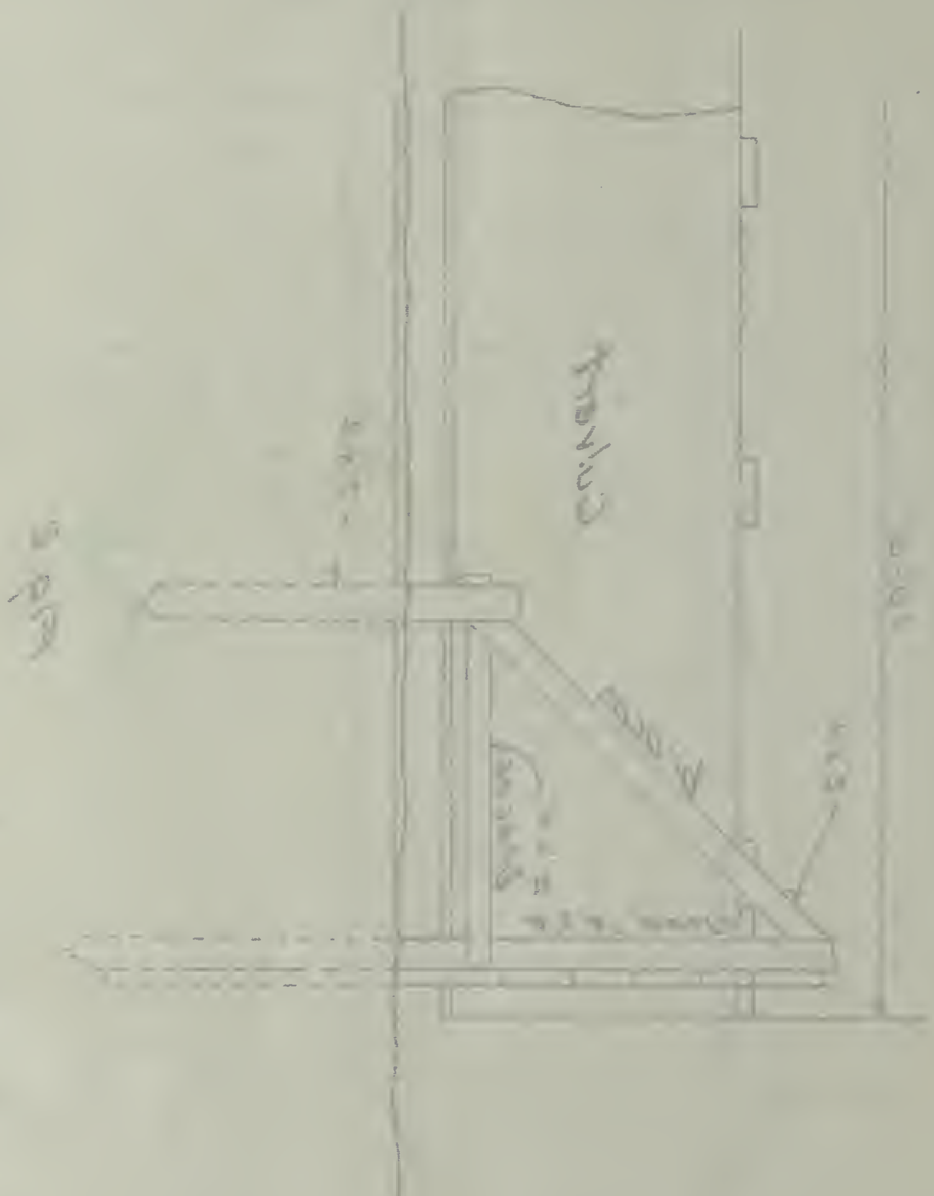
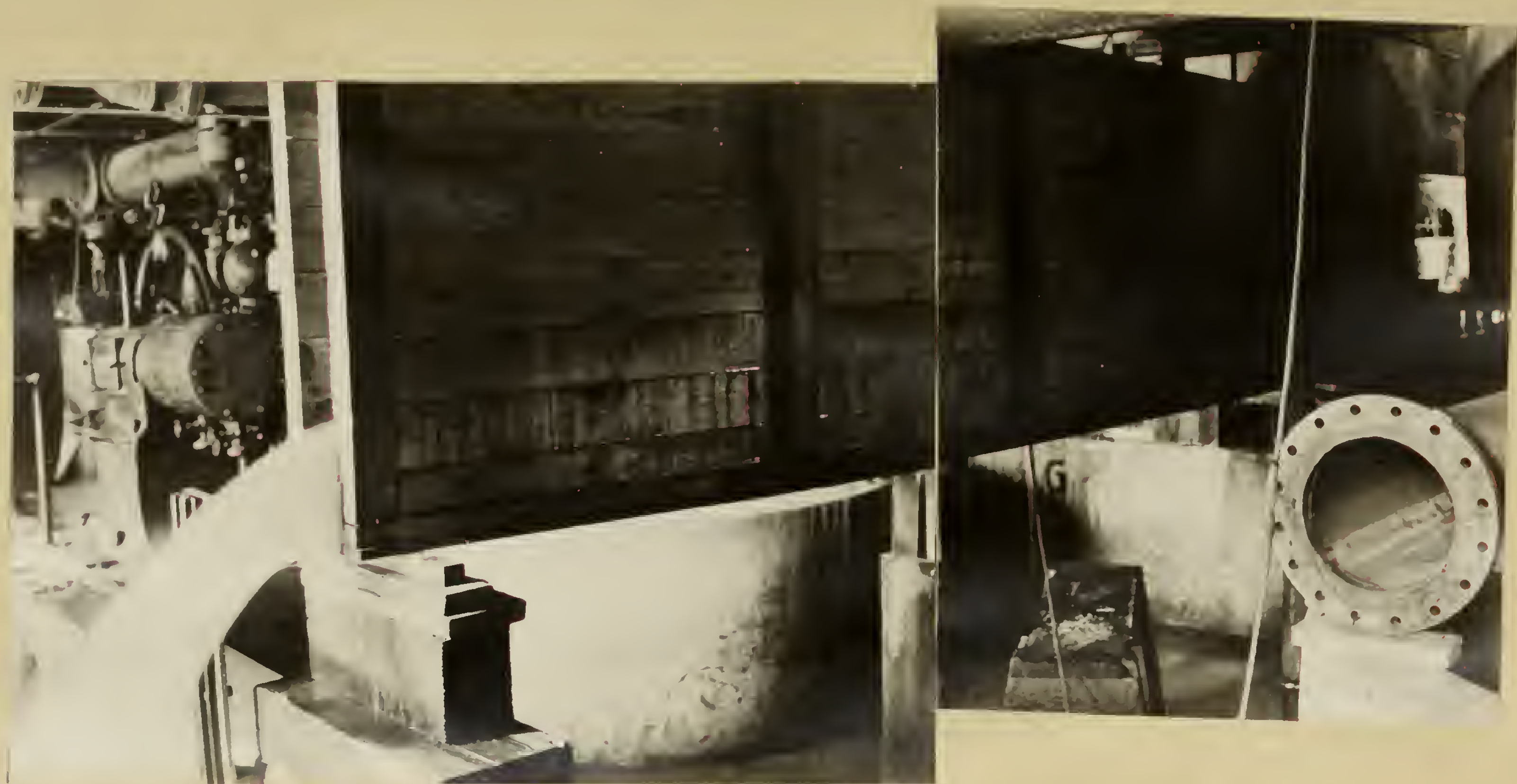


Fig. 2



View of Vertical jet used to measure Discharge of Culvert



View of Culvert-free outlet.

Scale for ¼'s 1in. = 4ft

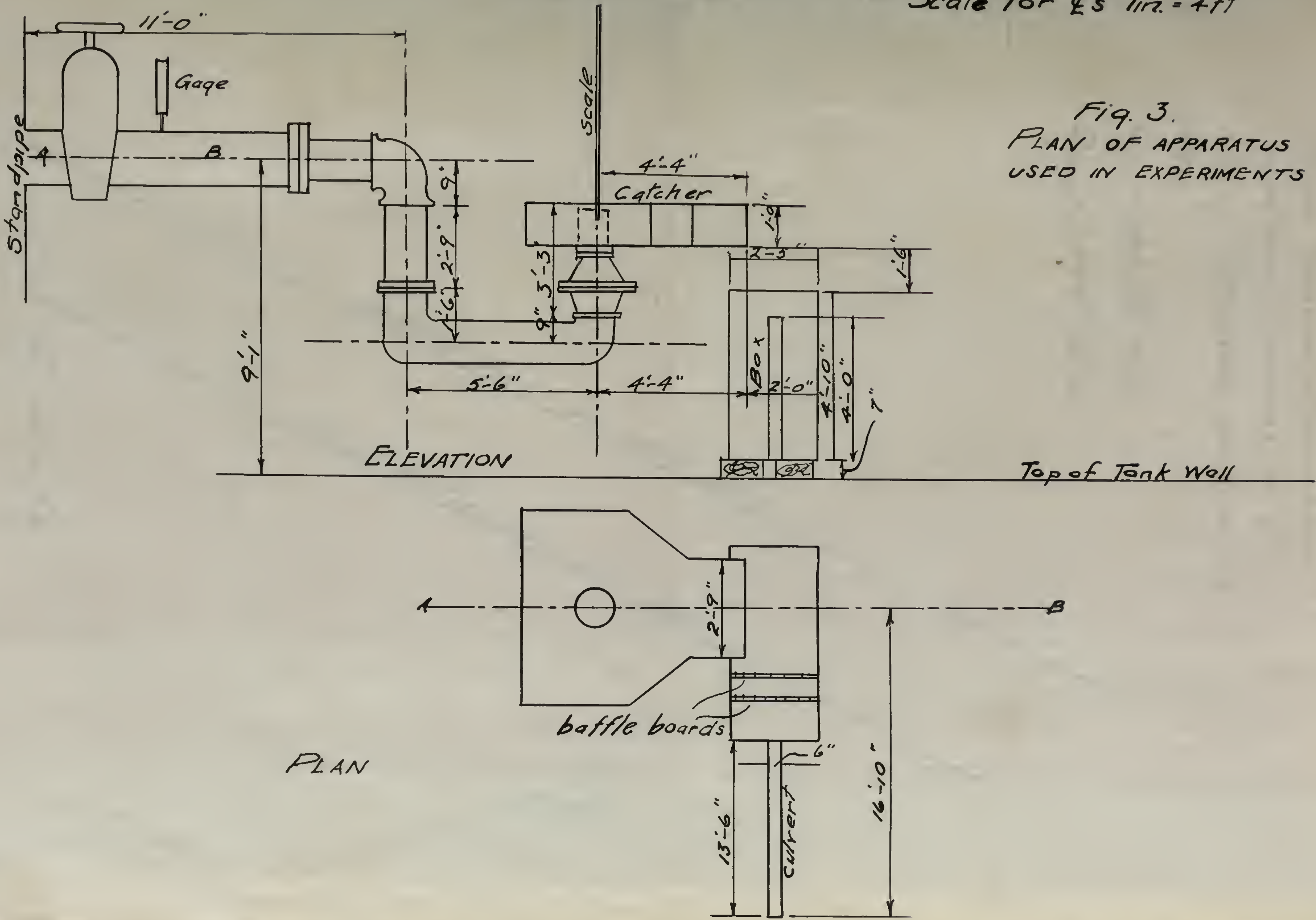
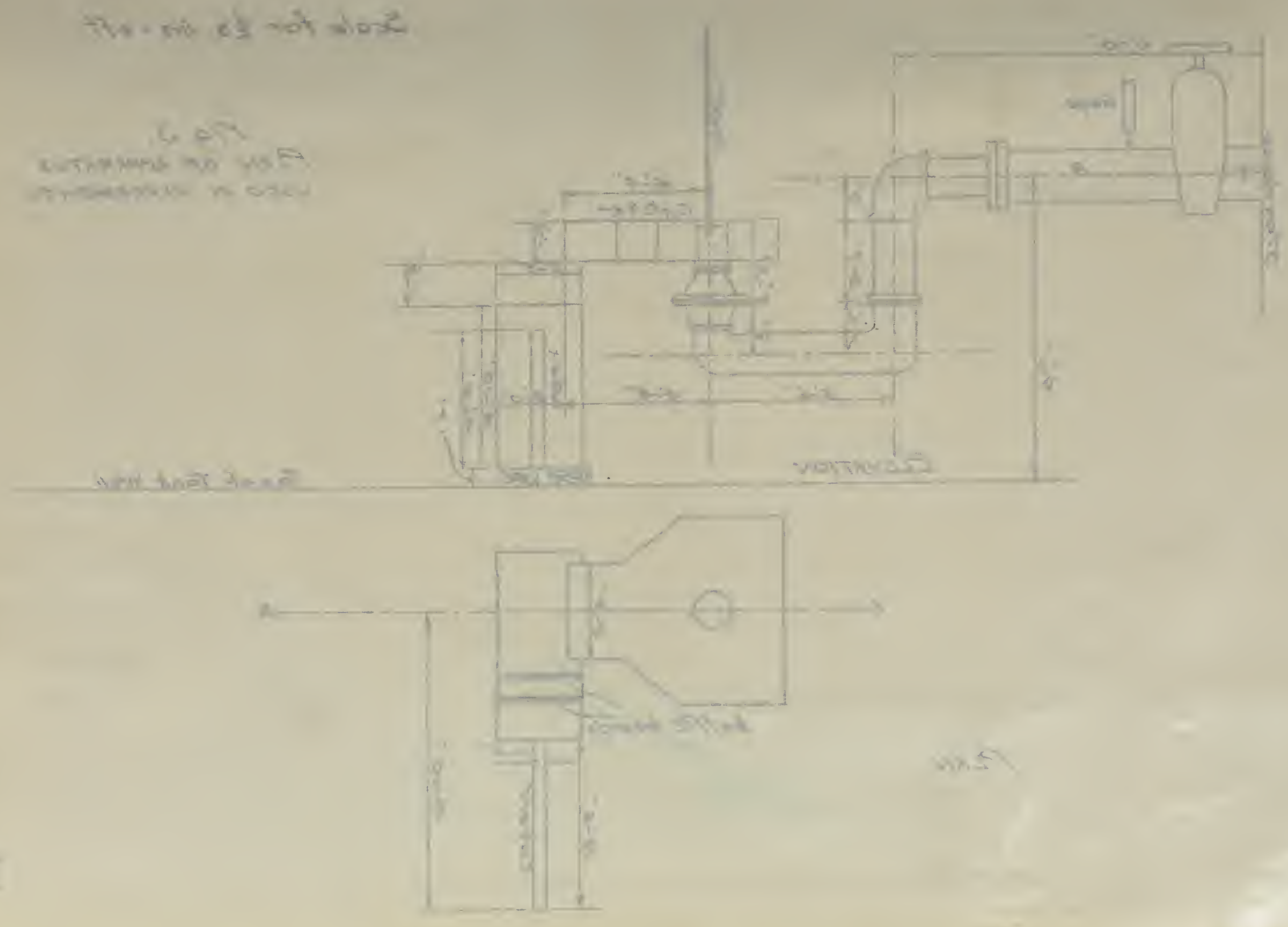


Fig. 3.
PLAN OF APPARATUS
USED IN EXPERIMENTS



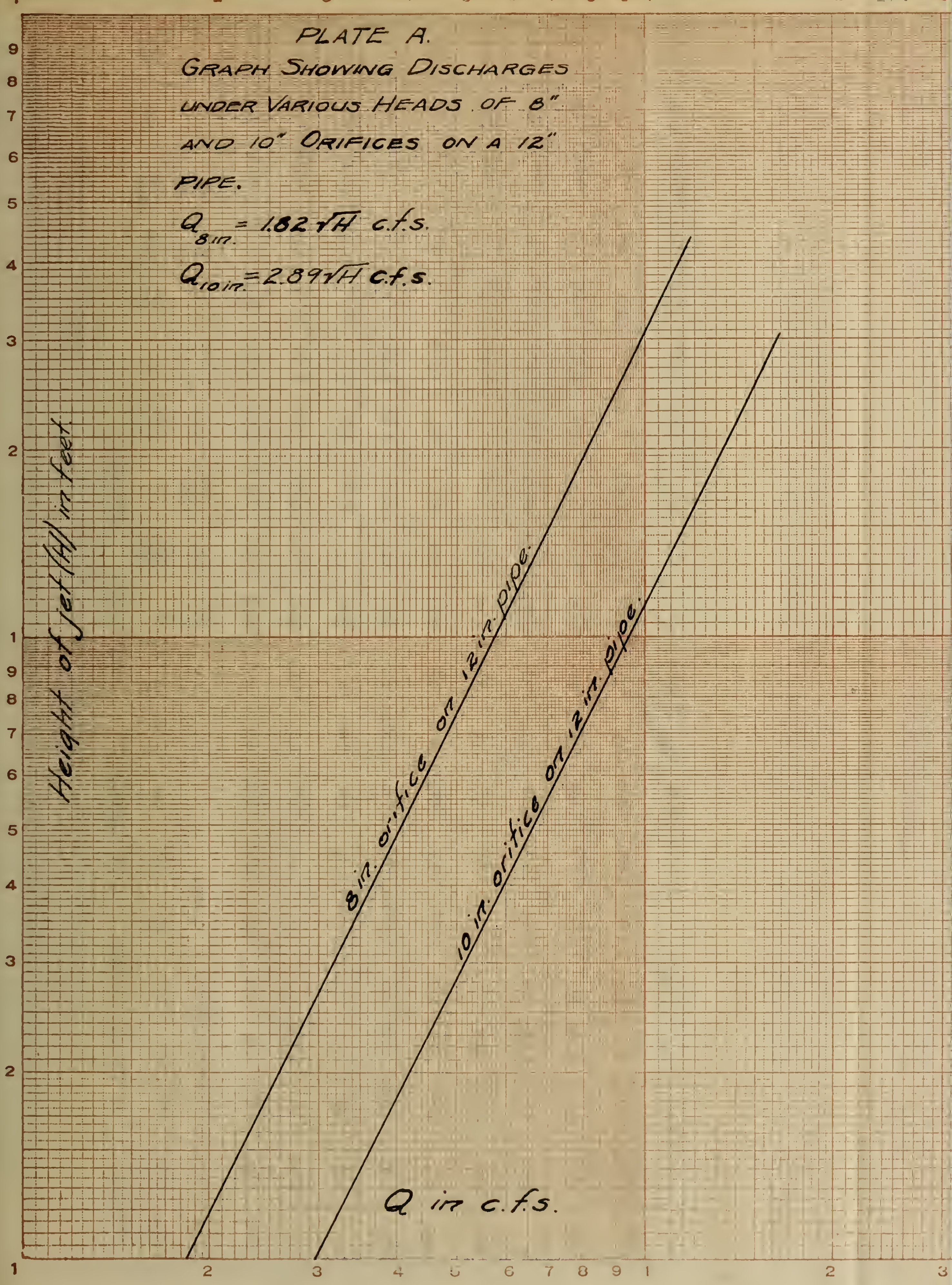


PLATE A.
GRAPH SHOWING DISCHARGES UNDER VARIOUS HEADS OF 8" AND 10" ORIFICES ON A 12" PIPE.
$Q_{8\,in.} = 1.82\sqrt{H}$ c.f.s.
$Q_{10\,in.} = 2.89\sqrt{H}$ c.f.s.
8 in. orifice on 12 in. pipe.
10 in. orifice on 12 in. pipe.
Height of jet (H) in feet.
Q in c.f.s.

Table I.

Culvert is 6 in. wide - 4 ft. deep opened outlet.

Ht.	Q	A_e	A_1	A_2	h_1	h_2	h	$h-h_1$	$h-h_2$	V_e	$\frac{V_e^2}{2g}$	V_1	$\frac{V_1^2}{2g}$	V_2	$\frac{V_2^2}{2g}$	$h-h_1-\frac{V_1^2}{2g}$	$h-h_2-\frac{V_2^2}{2g}$	e_1	e_2
ft.	c.f.s	square feet.			feet.			ft.	ft.	ft./sec.	ft.	ft./sec.	ft.	ft./sec.	ft.	ft.	ft.		
1.07	1.85	.625	.40	.538	.80	1.075	1.25	.45	.175	2.96	.136	4.62	.332	3.44	.183	.118	-.008	.87	-.059
1.7	2.35	.75	.475	.63	.95	1.25	1.50	.55	.25	3.14	.152	4.95	.380	3.74	.216	.170	.034	1.12	.224
2.1	2.6	.80	.50	.69	1.00	1.38	1.60	.60	.22	3.25	.164	5.2	.42	3.77	.22	.180	.00	1.10	.00
2.5	2.85	.825	.537	.72	1.075	1.43	1.65	.575	.22	3.46	.185	5.3	.436	3.96	.242	.139	-.022	.75	-.119
2.95	3.1	.925	.563	.76	1.125	1.53	1.85	.725	.32	3.35	.174	5.5	.47	4.08	.257	.255	.063	1.46	.362
3.05	3.15	.90	.55	.75	1.1	1.50	1.85	.75	.35	3.50	.190	5.73	.51	4.20	.272	.24	.078	1.26	.410
3.6	3.45	.95	.575	.78	1.15	1.55	1.90	.75	.35	3.63	.204	6.0	.56	4.42	.302	.19	.048	.93	.235
3.8	3.50	.95	.575	.80	1.15	1.60	1.90	.75	.30	3.69	.211	6.1	.58	4.38	.296	.17	.044	.805	.018
4.0	3.65	1.00	.60	.83	1.2	1.65	2.00	.80	.35	3.65	.207	6.08	.571	4.4	.30	.229	.05	1.11	.24
4.6	3.9	1.05	.60	.838	1.2	1.675	2.10	.90	.425	3.72	.214	6.5	.655	4.65	.334	.245	.091	1.14	.42

Table 2.

Culvert is 6 in. wide - 4 ft. deep. backwater of 1'-0".

Ht.	Q	A_E	A_1	A_2	h_1	h_2	h	$h-h_1$	$h-h_2$	V_e	$\frac{V_e^2}{2g}$	V_1	$\frac{V_1^2}{2g}$	V_2	$\frac{V_2^2}{2g}$	$h-h_1-\frac{V_1^2}{2g}$	$h-h_2-\frac{V_2^2}{2g}$	e_1	e_2
1.05	1.85	1.00	.95	.99	1.9	1.975	2.00	.1	.025	1.85	.053	1.95	.059	1.87	.054	.041	-.029	.775	-.55
2.1	2.6	1.125	1.025	1.13	2.05	2.25	2.25	.2	.00	2.31	.082	2.54	.100	2.30	.087	.100	-.087	1.21	-1.05
2.6	2.91	1.175	1.075	1.15	2.15	2.3	2.35	.2	.05	2.48	.095	2.71	.1075	2.53	.098	.0925	-.048	.975	-.506
3.05	3.15	1.2	1.10	1.19	2.2	2.37	2.4	.2	.03	2.62	.106	2.86	.127	2.64	.108	.073	-.078	.68	-.735
4.00	3.61	1.3	1.15	1.25	2.3	2.5	2.6	.3	.10	2.78	.119	3.14	.154	2.88	.128	.146	-.028	1.23	-.235

Table 3

Culvert is 6 in. wide - 2 ft. deep. free outlet.

1.65	3.8	1.00	.70	.815	1.4	1.63	2.05	.65	.42	3.8	.223	5.43	.455	4.66	.336	.195	.084	.875	.36
2.2	4.4	1.00	.79	.90	1.58	1.80	2.3	.72	.50	4.4	.300	5.56	.478	4.90	.371	.242	.129	.808	.43
2.7	4.85	1.00	.825	.97	1.65	1.94	2.65	1.00	.71	4.85	.364	5.88	.534	5.00	.386	.466	.032	1.28	.89
2.95	5.10	1.00	.84	1.00	1.68	2.00	2.72	1.04	.72	5.10	.402	6.07	.574	5.10	.403	.466	.317	1.16	.79

backwater of 1'-0".

.75	2.58	1.00	1.00	1.05	2.00	2.1	2.1	.1	.00	2.58	.103	2.58	.103	2.46	.094	-.003	-.094	-.003	-.91
1.05	3.05	1.00	1.05	1.11	2.10	2.22	2.48	.38	.24	3.03	.142	2.88	.128	2.73	.115	.252	.125	1.77	.88
1.7	3.85	1.00	1.223	1.37	2.45	2.75	3.175	.725	.425	3.85	.229	3.14	.153	2.81	.122	.572	.303	2.55	1.32

Table 4.

Ht.	Q	A_E	A_1	A_2	h_1	h_2	h	$h-h_1$	$h-h_2$	V_e	$\frac{V_e^2}{2g}$	V_1	$\frac{V_1^2}{2g}$	V_2	$\frac{V_2^2}{2g}$	$h-h_1-\frac{V_1^2}{2g}$	$h-h_2-\frac{V_2^2}{2g}$	e_1	e_2
.95	2.9	.75	.635	.675	1.27	1.35	1.75	.48	.40	3.86	.231	4.57	.323	4.3	.285	.157	.115	.68	.50
1.15	3.18	.75	.675	.725	1.35	1.45	1.87	.52	.42	4.24	.278	4.7	.342	4.38	.296	.178	.124	.64	.446
1.4	3.5	.75	.70	.785	1.4	1.57	2.04	.64	.47	4.67	.337	5.00	.386	4.46	.308	.254	.162	.75	.48
1.75	3.9	.75	.75	.875	1.5	1.75	2.05	.55	.30	5.20	.418	5.00	.418	4.46	.308	.132	-.008	-.316	-.019
2.15	4.45	.75	.75	.925	1.5	1.85	2.45	.95	.60	5.93	.544	5.93	.509	4.81	.358	.441	.242	.81	.445

Culvert is 6 in. wide - 1 ft. 6 in. deep. o free outlet.

Table 5

.48	2.06	.50	.425	.50	.85	1.00	1.2	.35	.2	4.12	.262	4.85	.364	4.12	.262	-.014	-.062	-.053	-.236
.71	2.51	.50	.475	.60	.95	1.2	1.3.	.35	.1	5.02	.389	5.28	.433	4.2	.273	-.083	-.173	-.21	-.445

Culvert is 6 in. wide - 1 ft. deep. free outlet.

Data for Plates 1 to 9

Measurements taken from 4 ft. above bottom of culvert to water surface.
From $7\frac{1}{2}$ ft. to end of culvert measurements taken 3'-1½" above bottom.

Ht.=height of jet. $Q_{8in.}=1.82\sqrt{Ht.}$ c.f.s. $Q_{10in.}=2.89\sqrt{Ht.}$ c.f.s. E=water surface before entrance.

Plate 1 - 8 in. nozzle

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14	
ft.	c.f.s.	inches																								
1.05	1.85		33	35¼	38¼	36½	35	35½	36	36¼	36½	36½	36¼	36½	36¾	37	37	26¼	26½		27½		28	28¾		
3.6	3.45		25	28	32	34	34¼	34¼	34	32¼	31¼	29¼	29½	31	32¾	32½	33	23	23	22¾	22½	23	24	25½		
4.6	3.90		23	26	31	32¼	33	33½	33½	32½	31½	30	28½	28	29	30	30¾	21	22	22¼	22½	22¾	23¼	24¼		
1.05	1.85		24	25¼	24½	24¼	24¼	24¼	24¼								24½				14¼		14½	15⅛	16	B

Plate 2 - 8 in. nozzle.

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14	
1.70	2.35		30	32¾	36	36½	34½	33	33	34	34¼	35	35	35	34½	34½	34½	24¼	24¾		25½		26	28		
2.95	3.10		26	29	33	34½	34½	34	32½	30½	29¾	31	32	32½	33	33¾	33½	22¾	22½		22		24½	26¼		
4.0	3.65		24	25¾	30	32¼	33½	33¾	33½	32¾	31½	29	28¼	29¼	29½	31	32	21¾	22¼		22½	22¾	23½	24¾		
4.0	3.65		17	20	20½	18½	18¾	18	18								18½				8		8¾	10	11¼	B

B = backwater of 1 ft. at outlet end.

Plate 3 - 8 in. nozzle

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14	
2.1	2.6		29	31½	34	36	34¼	32	31½	31½	32¼	33¼	33¾	34¼	34½	34	33¾	23	23¾		25		26	27½		
2.5	2.85		28	31	35	35	35	33½	31½	31	31½	32½	33	33½	33¾	33½	33¼	22½	22¼		24		25½	27		
2.1	2.60		21¼	22¾	23¼	22	21½	21½	21½							21¾					11½		12	12¾	13¾	B
2.6	2.91		20	22	21½	20¾	20½	20½	20¾								21				10¾		11¼	12¼	13¼	B

Plate 4 - 8 in. nozzle

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14	
3.05	3.15		26	29	33	34	34½	34¾	33½	32	30¼	30¼	31	32¼	32¾	33½	33½	23¼	22¾		22½		22	24½		
3.80	3.50		25	27¼	31¼	33½	34	34	34	33	32½	29½	28¾	30	30½	31¼	32	22¼	22¼	22¾	22¾	23	23¾	25		
3.05	3.15		19	21	21¼	20	19½	19½	19½								20				9½		10	11½	12½	B

Plate 5 - 10 in. nozzle

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14	
1.70	3.85	9	18½	17¾	17½	17	16½	15½	15¼	15½	15	15	15								4½		5½	7	8¼	B
.75	2.58	22	24	23¼	23	22¾	22¾	23													12¾		13¼	14	15	B
2.95	5.10	14½	24	23	25½	28	28	28	28	27½	26¼	25¾	24¼	24	24¼		25½		17		16		20¾	22	23¼	
2.20	4.40	19½	24	24½	28	29	28¼	29	29	28	27½	26¾	26¾	27¾	27¾	26½					20½		21½	23	24¼	
1.65	3.80	22½	24	26	28½	31	31	31¼	31	30	29¼	28½	28¼	29		30	30¼				22		23	24½	25½	

Plate 6- 10 in. nozzle.

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14
1.05	3.03	18½	23	22½	22	21½	21½	21½	21¾	21¾	21¾										12		12½	13¼	14¼ B
2.7	4.85	16½	24	24	26	28	28¼	28¼	28	27¾	27	26½	25	25	26¼	26½			18		20		21¼	22½	23½

Plate 7- 10 in. nozzle

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14
.48	2.06	33½	36	36	38	36½	36	36¼	36½	36¾	36¾	36¾	36½	37							27¾		28¼	29¼	30¼
.71	2.51	30½	36		36½	33½	34	34½	34¾	35	35	35	34¾	35	35						26		27¼	28½	29¼

Plate 8-10 in. nozzle.

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14
2.15	4.45	18½	30			29½	27½	26½	25¾	26	27	28	28	28½	30						19¼		21¼	23¼	24½
1.4	3.5	23½	30	29	30¾	29½	29¼	29½	29½	30	31	31½									22¼		24	25½	26¾
.95	2.9	27	30	30½	32¾	32	32	32	32	32¼	32½	33									24½		25¼	27	28

Plate 9-10 in. nozzle.

Ht.	Q	E	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14
1.75	3.9	20½	30			28½	27½	27	27½	27¾	29¼	30									20½	?	22½	24¼	25½
1.15	3.18	25½	30	30	31¾	31½	30½	30¾	31	31¼	31¾	31¾									23		24½	26¼	27¼

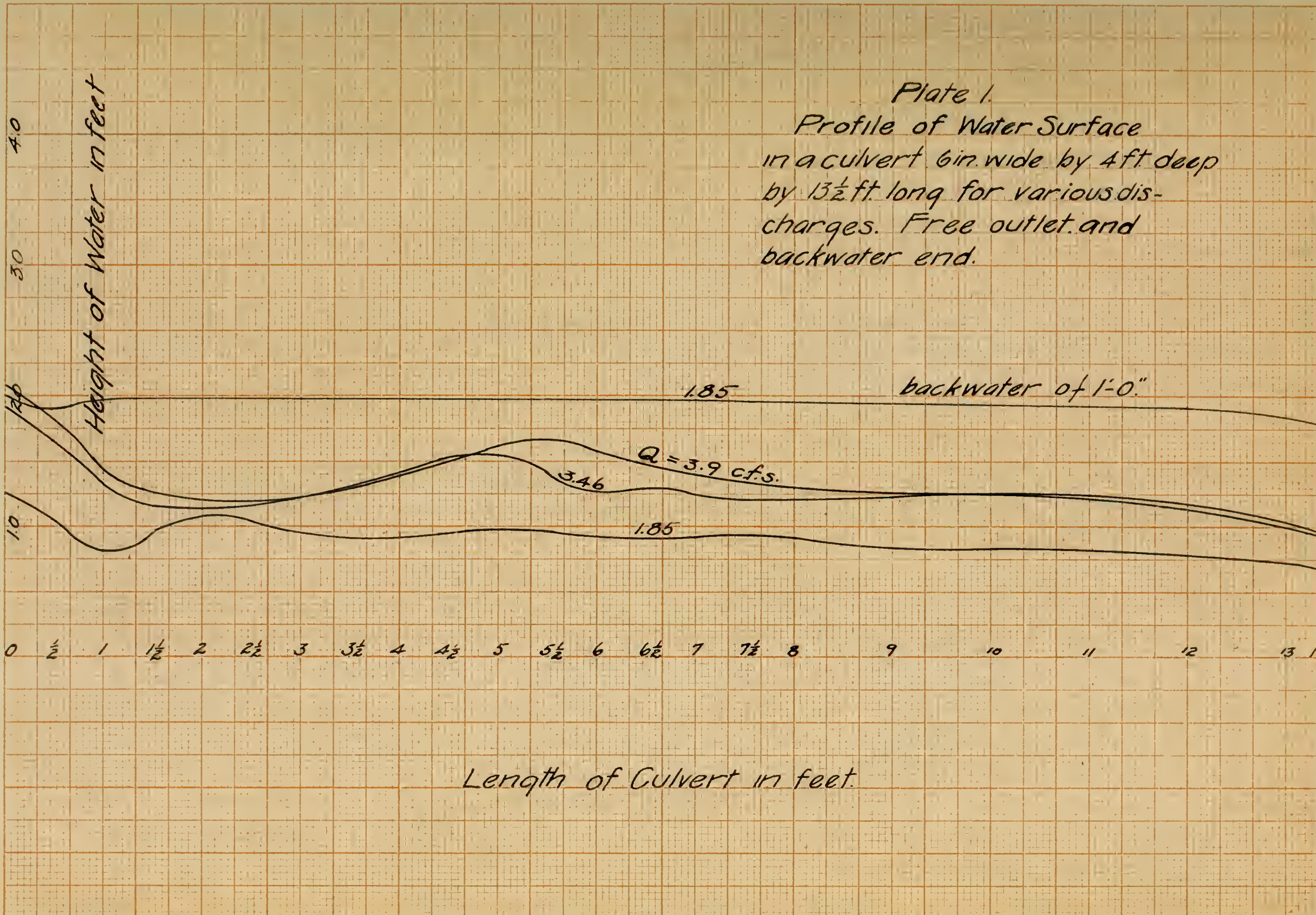


Plate 1.
Profile of Water Surface
in a culvert 6 in. wide by 4 ft. deep
by 13½ ft. long for various dis-
charges. Free outlet and
backwater end.
Height of Water in feet
4.0
3.0
2.0
1.0
1.85
backwater of 1'-0"
Q = 3.9 c.f.s.
3.46
1.85
0
½
1
1½
2
2½
3
3½
4
4½
5
5½
6
6½
7
7½
8
9
10
11
12
13
14
Length of Culvert in feet

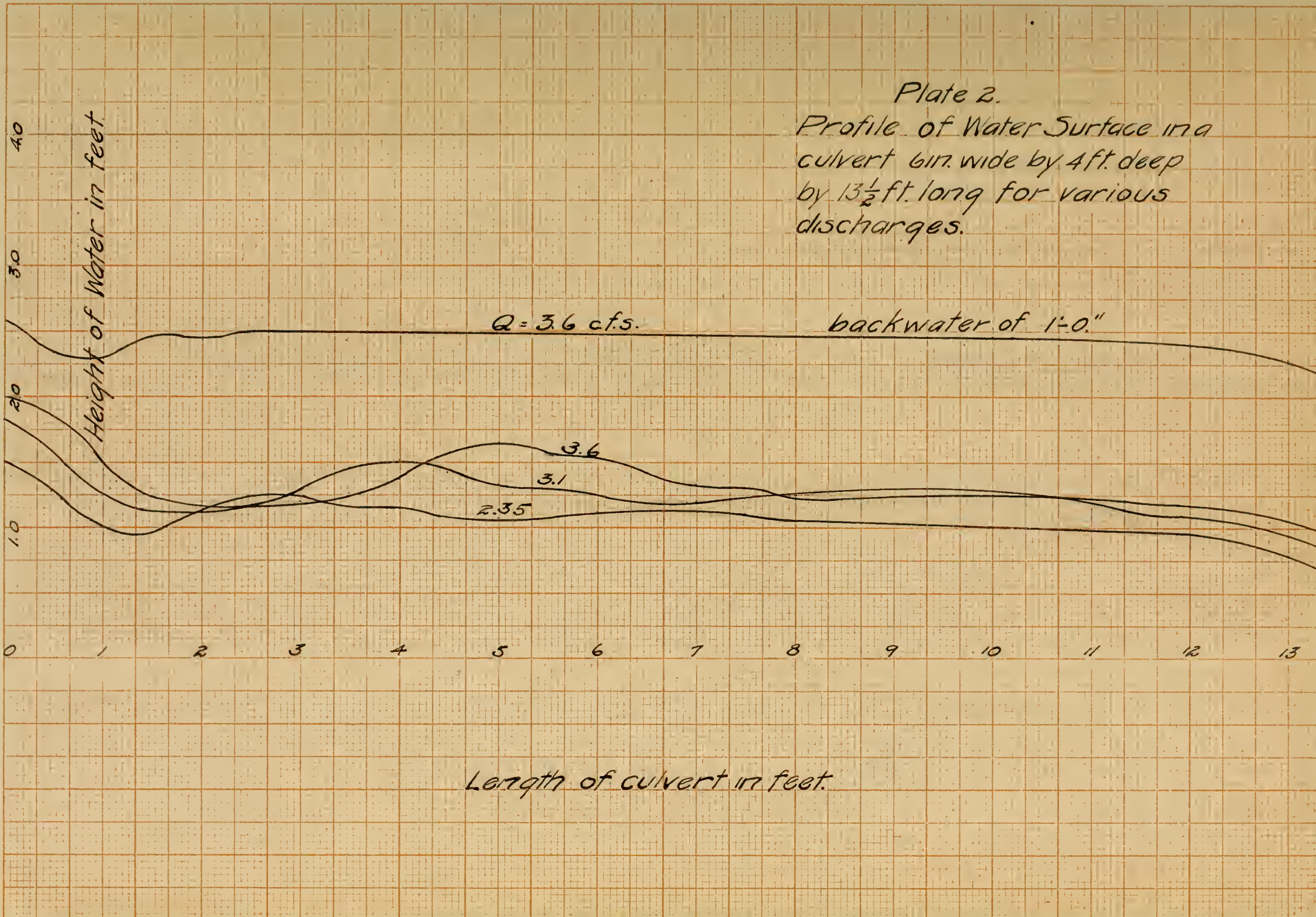


Plate 2.
Profile of Water Surface in a culvert 6 in. wide by 4 ft. deep by $13\frac{1}{2}$ ft. long for various discharges.

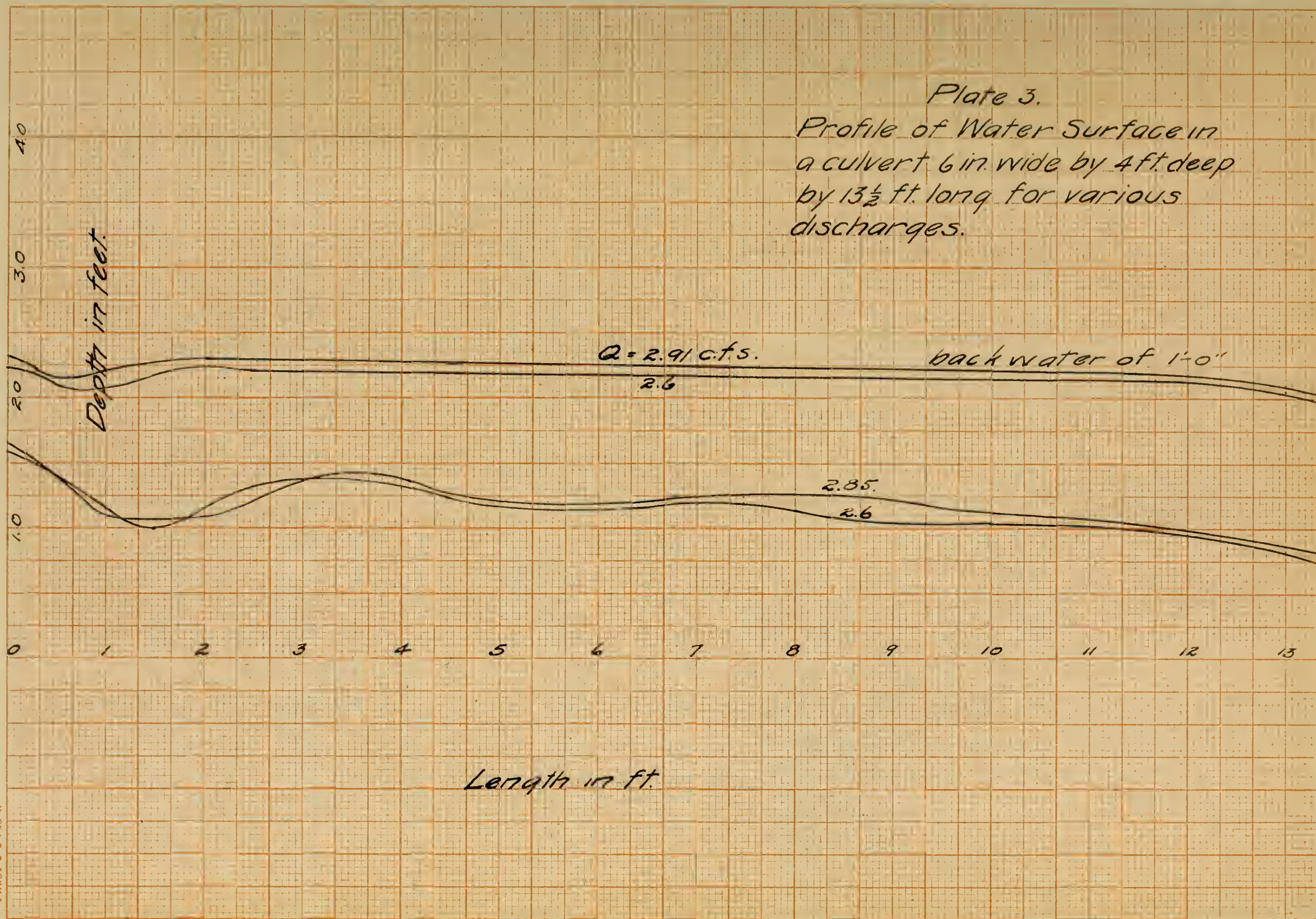


Plate 3.
Profile of Water Surface in a culvert 6 in. wide by 4 ft. deep by 13½ ft. long for various discharges.
Q = 2.91 c.f.s.
back water of 1'-0"
2.6
2.85.
2.6
Depth in feet.
4.0
3.0
2.0
1.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Length in ft.
U. OF I. S. S. FORM 3

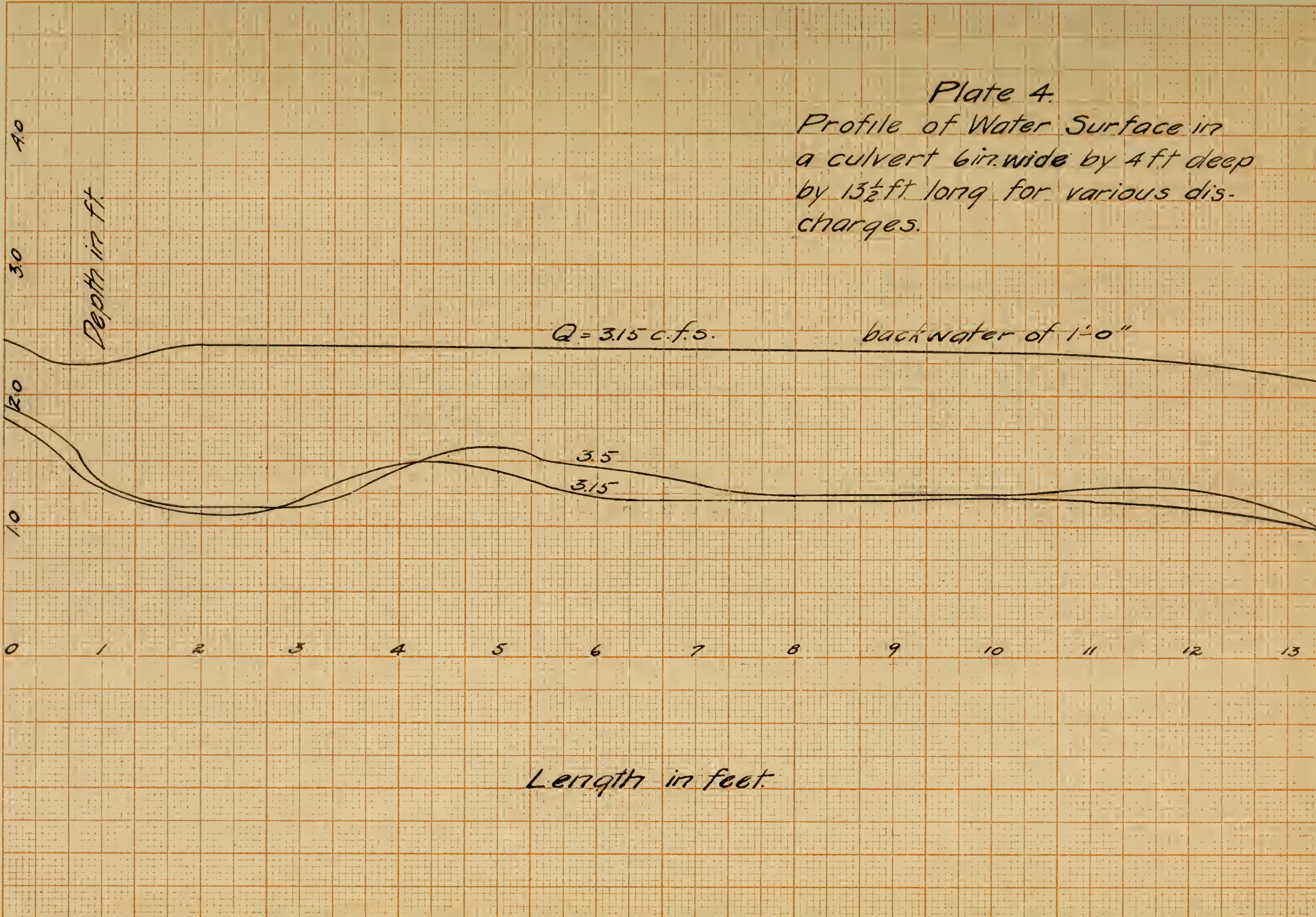


Plate 4.
Profile of Water Surface in a culvert 6 in. wide by 4 ft deep by $13\frac{1}{2}$ ft long for various discharges.

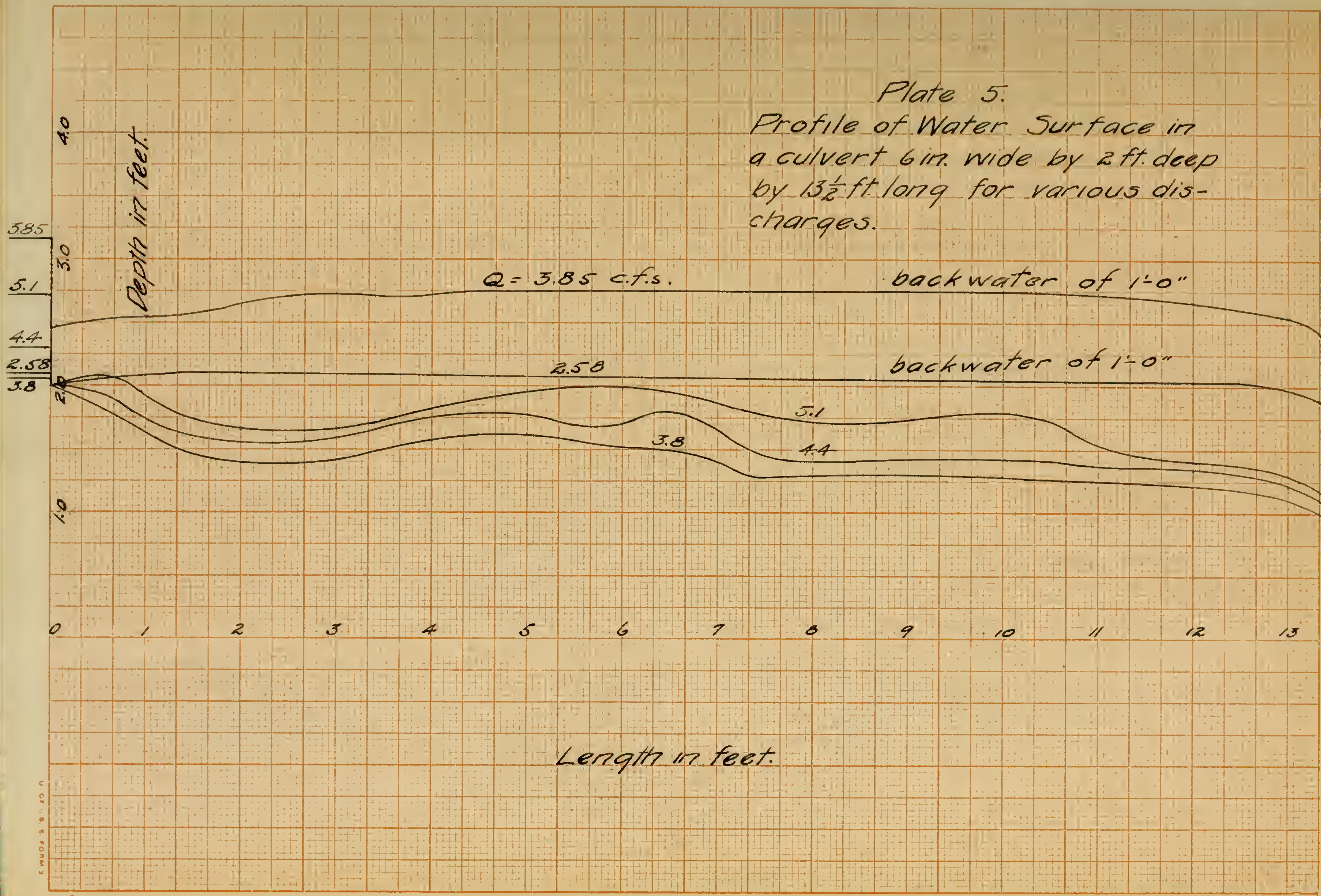


Plate 5.
Profile of Water Surface in a culvert 6 in. wide by 2 ft. deep by 13½ ft. long for various discharges.
Q = 3.85 c.f.s.
backwater of 1'-0"
backwater of 1'-0"
2.58
5.1
3.8
4.4
3.85
5.1
4.4
2.58
3.8
4.0
3.0
2.0
1.0
Depth in feet.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Length in feet.

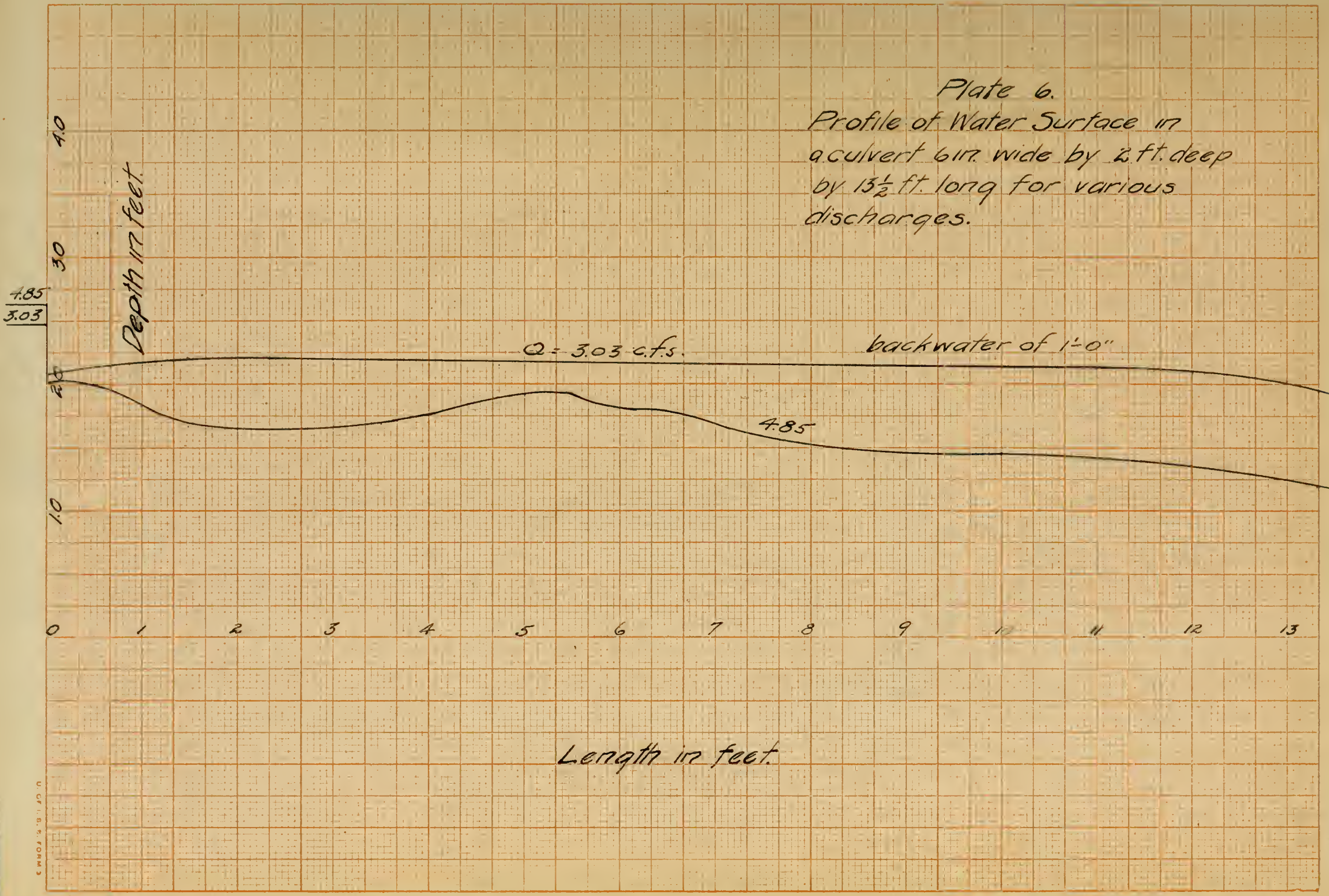


Plate 6.
Profile of Water Surface in
a culvert 6 in. wide by 2 ft. deep
by 13½ ft. long for various
discharges.
Depth in feet.
4.0
3.0
2.0
1.0
4.85
3.03
Q = 3.03 c.f.s.
backwater of 1'-0"
4.85
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Length in feet.
U. OF I. S. S. FORM 3

Plate 7.

Profile of Water Surface in a culvert 6 in. wide by 1.0 ft deep by $13\frac{1}{2}$ ft. long for various discharges.

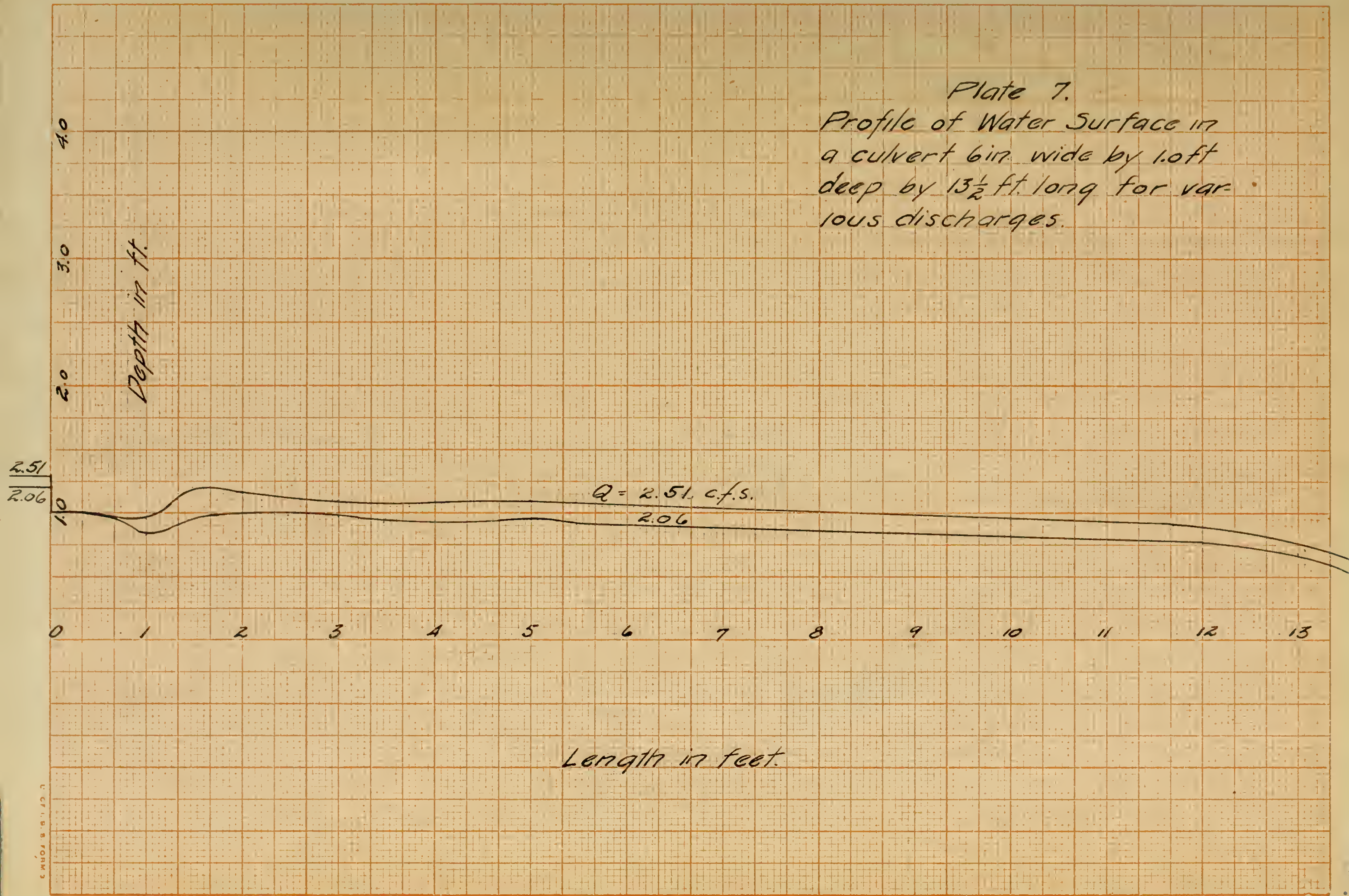
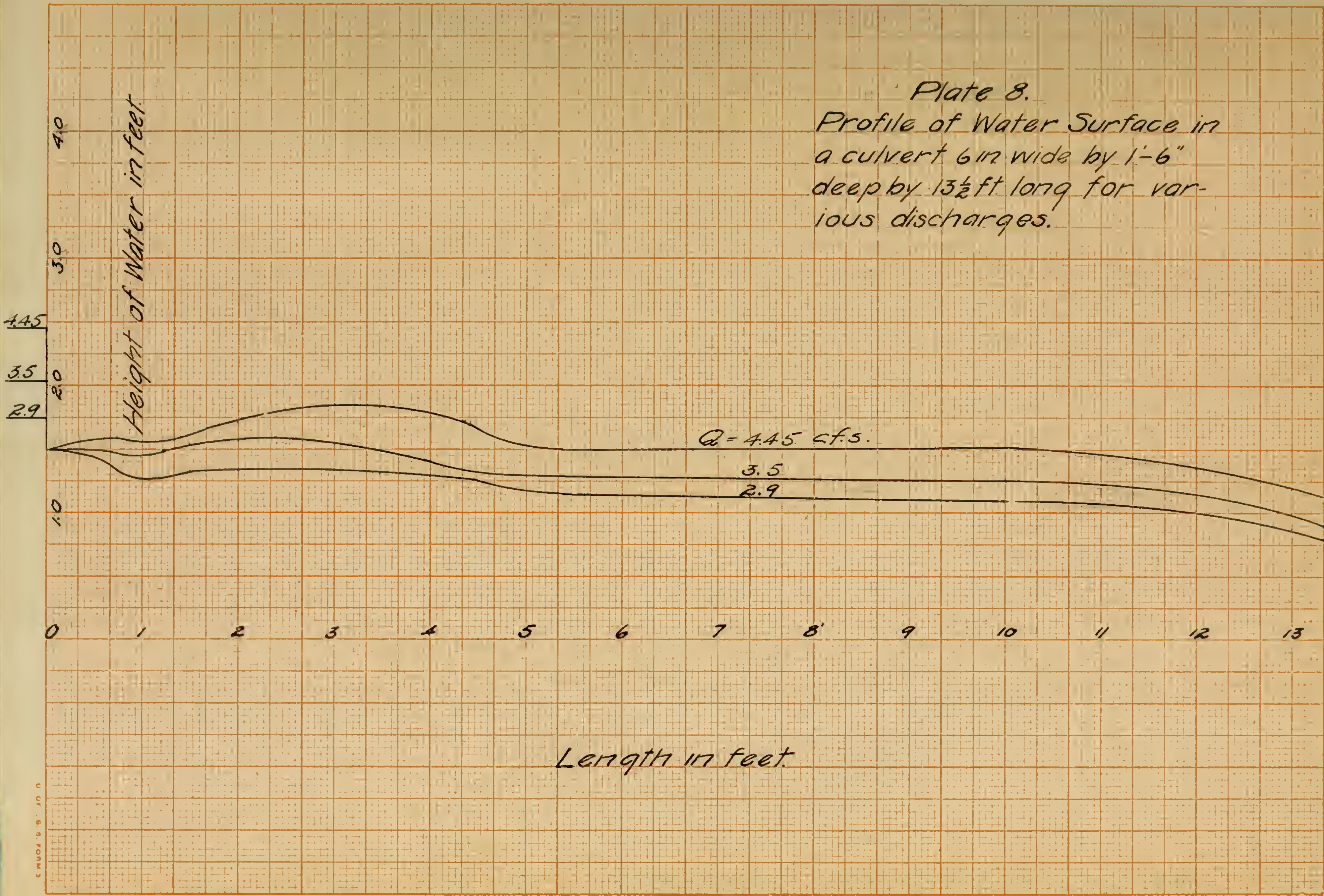


Plate 8.

Profile of Water Surface in a culvert 6 in wide by 1'-6" deep by $13\frac{1}{2}$ ft long for various discharges.



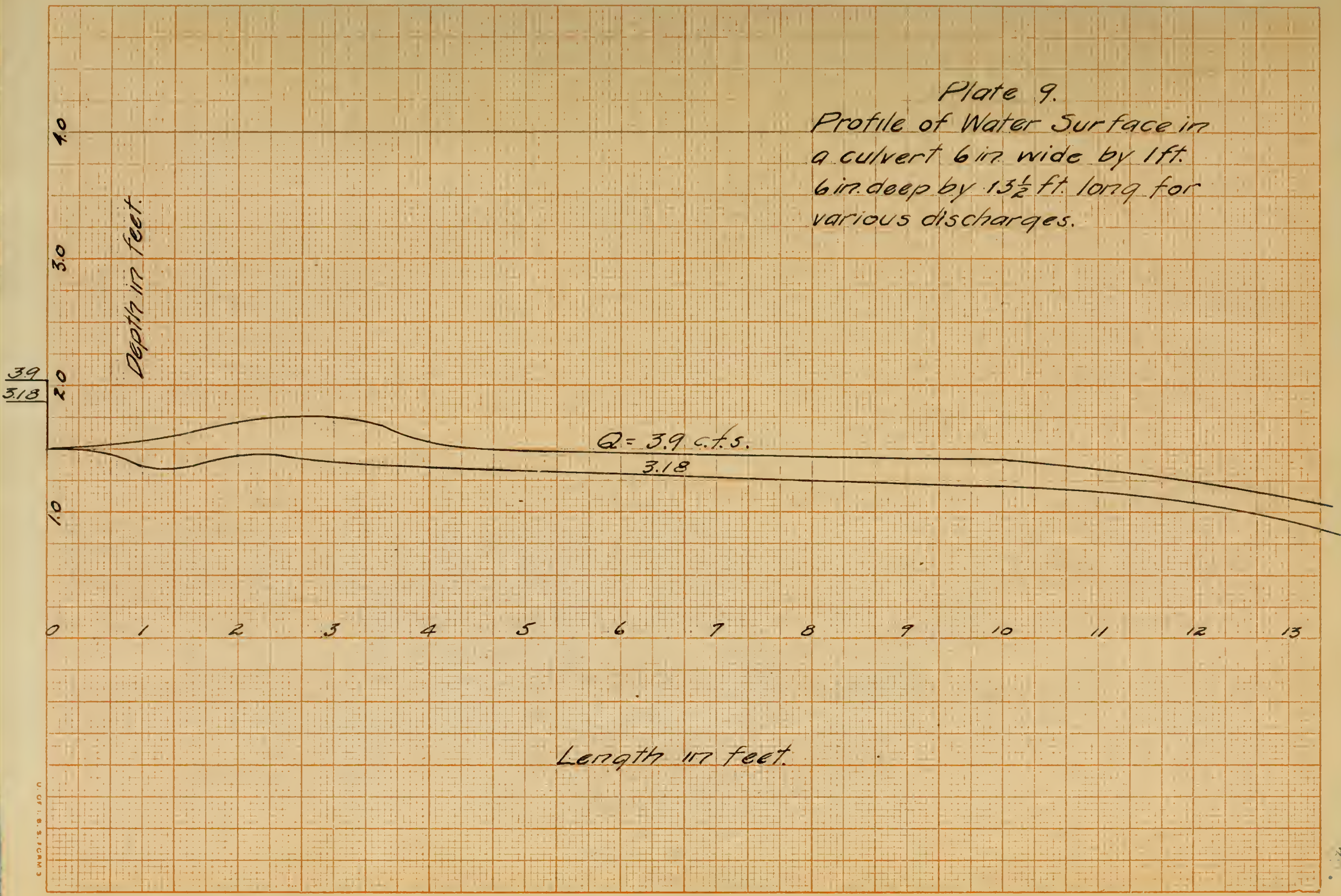


Plate 9.
Profile of Water Surface in a culvert 6 in. wide by 1 ft. 6 in. deep by 13½ ft. long for various discharges.
Depth in feet.
4.0
3.0
2.0
1.0
3.9
3.18
Q = 3.9 c.f.s.
3.18
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Length in feet.
U. OF I. S. S. FORM 3